

Effects of Drilling Muds and Mud Additives on the Primary Production of Natural Assemblages of Marine Phytoplankton

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ABSTRACT

The effects of two types of drilling mud and eight mud additives on the primary production of natural assemblages of marine phytoplankton from the Santa Barbara Channel, California, were examined. Exposure for 4 h to BaSO₄, Ca-, Cr- and Fe- lignosulfonate, Drispac (a polyanionic cellulose polymer), X-Pel-G (gilsonite), Soltex (a sulfonated asphalt) and a synthetic reference drilling mud at concentrations ranging over seven orders of magnitude did not significantly alter primary production of phytoplankton relative to untreated controls. A used drilling mud from the Santa Barbara Channel significantly enhanced primary production of phytoplankton exposed for 4 h to mud diluted by a factor of 10¹ to 10⁷. Exposure for up to 120 h to low concentrations of BaSO₄, iron-lignosulfonate, paraformaldehyde and both the reference drilling mud and used Santa Barbara mud did not significantly alter primary production. Long-term exposure to Soltex and gilsonite significantly reduced primary production, but only at exposure times considerably longer than would be expected in nature. Drispac enhanced primary production by 50% after exposure for 120 h to 1 µg liter⁻¹. Phytoplankton composition was not altered by long-term exposure to the muds or additives. These results suggest that, where dilution is rapid, discharge of muds containing the additives studied here would not significantly alter the primary production of natural phytoplankton assemblages in the vicinity of drilling platforms.

INTRODUCTION

The expansion of the offshore oil industry in recent years has resulted in increased discharge of drilling muds and cuttings into the ocean and stimulated concern regarding the impact of drilling fluids on the biology of marine organisms. Drilling muds are used in rotary drilling for oil and gas to remove cuttings, to cool and lubricate the drill string and to seal and control pressure in the well. They are composed primarily of water, barium sulphate, clay minerals, lignosulfonates and additional additives including biocides and lubricants. Most research on the biological impacts of drilling muds and their components has focused on determining the acute lethal toxicities of muds to individual species of marine organisms (see National Research Council, 1983 for review). Little is known regarding the chronic or sublethal effects of discharged drilling fluids on marine animals and even less is known regarding the impact of these drilling muds on the primary production of marine plants, especially phytoplankton.

Carbon fixation by marine phytoplankton is the major energy source for many marine communities. Thus, pollutants which reduce primary production of phytoplankton may impact marine communities at all trophic levels. A few previous studies suggest that high concentrations of petroleum and petroleum products are highly toxic to phytoplankton, but low concentrations ($\mu\text{g liter}^{-1}$) may occasionally enhance primary production (Gordon & Prouse, 1973; Pulich *et al.*, 1974; Parsons & Waters, 1976). Similar data regarding the effects of drilling muds and their components on marine phytoplankton is needed in order to more fully understand the potential ecological impacts of ocean dumping and to provide information on which to base management and regulatory decisions.

In the following study we investigated the effects of mud additives and whole drilling muds from a well in the Santa Barbara Channel, California, on the ^{14}C uptake and taxonomic composition of natural assemblages of coastal marine phytoplankton. Our experimental approach was twofold. First, we measured the primary production of phytoplankton exposed for less than 4 h to concentrations of muds and additives ranging over seven orders of magnitude. Short-term exposure was designed to investigate the maximum potential impact following bulk discharges of drilling muds. Secondly, we measured the primary production of phytoplankton, exposed for varying intervals up to 120 h, to

low concentrations of muds and additives. Maximum exposures were longer than might be expected in nature (National Research Council, 1983) in order to investigate maximum possible effects.

MATERIALS AND METHODS

Unfiltered seawater containing undisturbed, natural assemblages of phytoplankton was collected from the seawater system at the Marine Laboratory of the University of California, Santa Barbara. This water originated 200 m offshore due south of the Santa Barbara campus at a depth of 10 m. We intercepted the seawater at a point where the intake pipe joined the land, within seconds of its entry into the seawater system from the ocean and prior to its passage through any pumps.

We collected used drilling muds and cuttings on the exploratory drilling rig, Key Singapore, operating at the west end of the Santa Barbara Channel, 5 km south of Point Arguello, California, on 23 August, 1984. The drilling fluids originated from a single well drilled to a depth of 1024 m in the Lower Sisquoc formation. The muds and cuttings had been circulated at least three times through the well and were collected in 4-liter, acid washed polyethylene bottles from the return flow line of the well. Used drilling muds were stored, unopened, at 4°C and tested within 30 days of collection.

Freshly collected used mud weighed 1140 g liter⁻¹ and was 92 % water and 8 % solids by volume. The mud had a pH of 9.5 and contained barium sulfate (approximately 100 g liter⁻¹), bentonite (approximately 75 g liter⁻¹), iron-chelated lignosulfonate (approximately 25 g liter⁻¹), caustic soda (approximately 10 g liter⁻¹) and a polyanionic cellulose polymer (trade name, Drispac: Baroid Corporation; approximately 10 g liter⁻¹). These concentrations were calculated from data supplied by the mud engineer of the Key Singapore.

The liquid phase of the used muds was prepared for testing following a standard procedure recommended by the American Petroleum Institute (1984). First, the mud was thoroughly mixed on a magnetic stirrer for 30 min. We then mixed one part mud to nine parts Millipore-filtered (0.45 μ pore size) natural seawater by volume. The pH of the resulting slurry was adjusted to that of the natural seawater (7.8) by the addition of concentrated HCl. The slurry was mixed with a magnetic stirrer for 30 min and then allowed to settle for 1 h. Part of the supernatant, or

suspended particulate phase, was then decanted off and filtered through a 0.45 μm Gelman filter to obtain the liquid phase. These phases were serially diluted with natural seawater to obtain the needed concentrations.

We also tested a Reference Drilling Mud prepared by the National Bureau of Standards using commercially available components (sample code RDM0802). This mud was prepared for experimentation according to Environmental Protection Agency instructions by mixing 0.5 kg dry

TABLE 1
Elemental Composition of Dry Reference Mud Prepared
by the Bureau of Standards from Commercially Available
Components (Sample No. RDM0802)
(Data courtesy of L. T. McClendon, Office of Environ-
mental Measurements, Washington, DC)

<i>Element</i>	<i>Concentration</i> (mg per kilogram of dry mud)
K	2 100 \pm 200
Fe	8 500 \pm 500
Cr	2 800 \pm 200
Si	161 000 \pm 2 000
Ca	2 900 \pm 200
Ba	381 800 \pm 4 000
Al	21 800 \pm 1 000

mud with 2.0 g NaOH and 750 ml deionized water. Mud was prepared and stirred overnight (12 h) with aeration on a magnetic stirrer prior to use. The elemental constituents of this prepared synthetic mud are shown in Table 1. The suspended particulate and liquid phases of the reference mud were then prepared and diluted as described for used mud.

Mud additives, including chrome-free, iron-chelated lignosulfonate (trade name—Ferro-Cal: Milchem Corporation), sulfonated asphalt (trade name—Soltex: American Mud Company), polyanionic cellulose polymer (trade name—Drispac: Baroid) and gilsonite (trade name—X-Pel-G: American Mud Company) were obtained from the Key Singapore in their dry, premixed state. Additional additives, including BaSO_4 , calcium lignosulfonate, chrome lignosulfonate and paraformaldehyde, were purchased commercially.

Short-term effects

We measured the primary production of natural phytoplankton during the first 2 to 4 h of exposure to drilling muds and additives at concentrations ranging over seven orders of magnitude. For each experiment a large, homogeneous seawater sample was divided into eight treatment groups, each containing three light and two dark replicates (10 or 50 ml each). In some cases, where undissolved particles remained, one additional replicate containing 0.2 % formalin as a control for absorption was included in each treatment group. No additives were added to one treatment group which served as a seawater control. In the case of soluble additives (liquid phase of whole muds, Drispac, lignosulfonate), the treatments were made by serially diluting the highest concentration with natural seawater. Less soluble additives (BaSO_4 , Soltex, X-Pel-G) were added to each treatment group at the appropriate concentration as dry components. Seawater samples were all placed in polycarbonate bottles or glass test tubes washed as described by Fitzwater *et al.* (1978) to reduce contamination by heavy metals.

Primary production was determined as described in Strickland & Parsons (1972). Immediately following addition of the additive, ^{14}C -bicarbonate was added to each sample for a final concentration of $0.4 \mu\text{Ci ml}^{-1}$. Light and dark replicates were incubated for 2 to 4 h at ambient seawater temperature (15°C) over a $125 \mu\text{E m}^{-2} \text{s}^{-1}$ light bank or in the dark, respectively. After incubation, photosynthesis was stopped by placing the samples in the dark on ice. Each sample was then filtered through a $0.45 \mu\text{m}$ pore size |Metricel| filter, rinsed with filtered seawater, fumed over HCl for 1 to 2 min and placed in scintillation vials containing 10 ml Liquescent scintillation cocktail (National Diagnostics). Radioactivity was measured on a Beckman LS6800 Scintillation Counter.

Calcium-, iron- and chrome-lignosulfonate all produced highly pigmented solutions requiring an additional set of controls to determine the effects of light occlusion. These controls consisted of natural seawater samples incubated on the light bank over filters made from the seven experimental concentrations of lignosulfonates. Each filter had opaque sides, a transparent top and bottom and contained lignosulfonate solution of the same concentration as the corresponding experimental treatment but at half the depth. Thus, seawater controls experienced light quality and intensity equal to the 'average' light experienced by the experimental treatments.

Long-term exposure

We also measured the primary production of phytoplankton exposed to drilling fluids and additives for periods up to 120 h. For these measurements, 1 liter of fresh seawater was placed in each of four unsealed Fernbach flasks and three different concentrations of additive were then added to three of the flasks. All flasks were placed on a 12 h light-dark cycle under identical conditions and mild agitation at 15°C.

Primary production was measured daily at 0900 h, as described previously. Six 10-ml samples from each flask were pipetted into 20-ml cleaned glass test tubes and inoculated with ^{14}C -bicarbonate at concentrations of 0.2 to 0.3 $\mu\text{Ci ml}^{-1}$. Three tubes were incubated in the dark and three in the light ($125 \mu\text{E m}^{-2} \text{s}^{-1}$) for 2 to 3 h at 15°C. After incubation, the tubes were filtered as described above. Controls for light occlusion were not used in studies of the long-term effects of highly pigmented additives because these additives were tested at concentrations too low to produce significant pigmentation.

Differences in the mean primary production between treatments were tested using the Kruskal-Wallis test and the Mann-Whitney U test, both non-parametric tests appropriate for the small number of replicates in each treatment (Sokal & Rohlf, 1969).

Twenty milliliters of phytoplankton samples from the seawater control and from one experimental flask were removed at 0 and 120 h during some of the experiments. These samples were preserved in 1 % Lugol's solution until the phytoplankton could be concentrated onto microscopic slides using the filter-freeze-transfer (FFT) technique (Hewes & Holm-Hanson, 1983). Phytoplankton were identified to major taxonomic category on twenty fields of each slide preparation and the phytoplankton concentration and composition calculated.

RESULTS

The absolute value of the ^{14}C uptake of samples incubated for several days in the laboratory varied considerably over time, even in control samples. However, throughout this paper we will be concerned with the *relative* differences in ^{14}C uptake between experimental and control treatments, rather than with absolute values of primary production. We observed three major effects of exposure to various drilling muds and mud

additives on the primary production of natural phytoplankton: (1) significant reduction of ^{14}C uptake; (2) no effect on ^{14}C uptake at low concentrations of additives and (3) significant enhancement of ^{14}C uptake.

Significant reduction of ^{14}C uptake

Additives were assigned to this category only when long-term effects were observed at low concentrations of additives.

Soltex

Soltex, a sulfonated asphalt, is a borehole stabilizer and lubricant in drilling muds. The ^{14}C uptake of samples exposed to Soltex for less than 4 h was not significantly different from that of untreated controls at concentrations from 0 to 1000 mg of Soltex per liter. However, significant long-term effects of Soltex were observed. ^{14}C uptake of phytoplankton was reduced to only 10% of that of untreated controls within 24 h of continuous exposure to Soltex at 100% saturation (Soltex added in excess to flask) (Fig. 1; $P < 0.05$). By 72 h ^{14}C uptake was significantly lowered by exposure to medium concentrations of 1 mg of Soltex per liter. By 96 h,

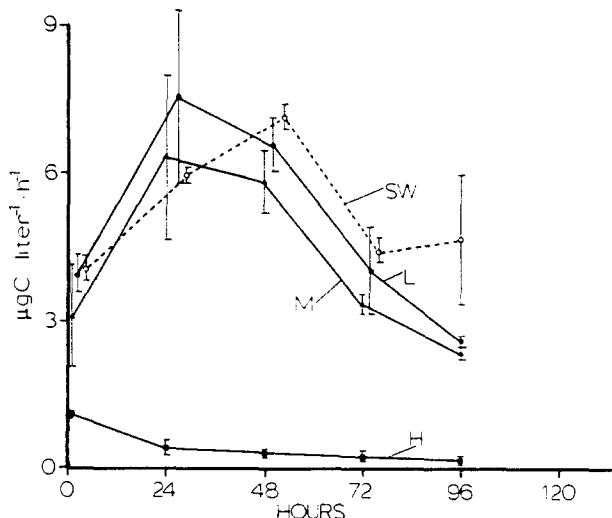


Fig. 1. Long-term effects of three concentrations of Soltex on primary production of phytoplankton. Data points are Light-Dark treatment means \pm one standard deviation. High (H) = 100% saturation; Medium (M) = 1 mg liter $^{-1}$; Low (L) = 0.01 mg liter $^{-1}$; Seawater (SW) = untreated control.

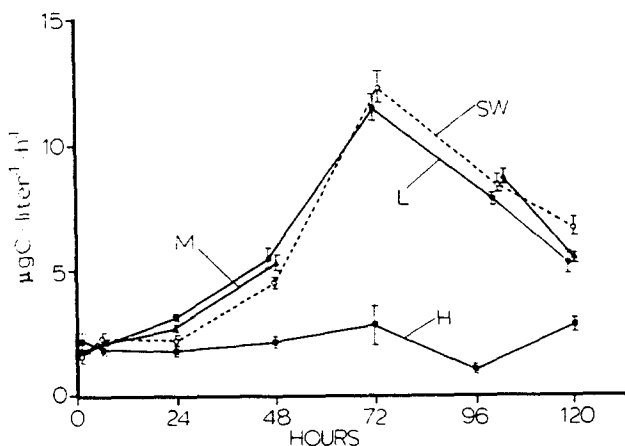


Fig. 2. Effects of three concentrations of X-Pel-G on the primary production of phytoplankton exposed for up to 120 h. Data points are Light-Dark treatment means \pm one standard deviation. H = 100 mg liter⁻¹; M = 1 mg liter⁻¹; L = 0.01 mg liter⁻¹; SW = untreated control.

exposure to 10 μ g of Soltex per liter resulted in significant reduction of primary production relative to untreated controls (Fig. 1; $P < 0.05$).

X-Pel-G

Exposure to X-Pel-G, the trade name for gilsonite, another stabilizer and lubricant, at concentrations from 0 to 100 mg of X-Pel-G per liter for less than 4 h did not result in a significant change in primary production relative to untreated controls. However, long-term exposure to 100 mg of X-Pel-G per liter decreased primary production of phytoplankton by a factor of 3 within 48 h ($P < 0.05$). By 120 h, exposure to 10 μ g of X-Pel-G per liter resulted in significant reduction of primary production of phytoplankton ($P < 0.05$; Fig. 2).

No significant effect on ¹⁴C uptake

Additives were assigned to this category if no significant effects were observed at the lowest concentration of additive.

Reference mud

Exposure to the liquid phase of the synthetic reference mud for less than 4 h resulted in significant reduction ($P < 0.05$) of ¹⁴C uptake only when diluted less than 10³ times (Fig. 3A). Exposure to the suspended

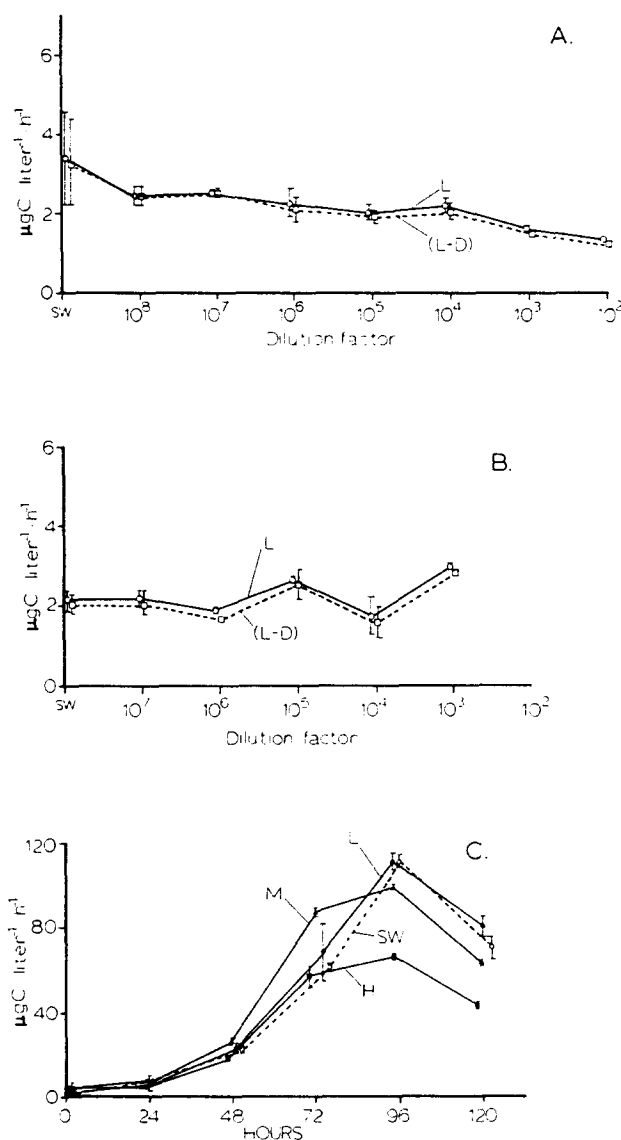


Fig. 3. Mean (\pm one standard deviation) effect of synthetic mud on the primary production of phytoplankton. A. Effects of the liquid phase after less than 4 h exposure to seven different dilutions. L = light. D = dark. B. Effects of the suspended particulate phase after less than 4 h exposure to five dilutions. C. Long-term effects after exposure for up to 120 h to synthetic mud at four concentrations: H = 10^3 dilution; M = 10^4 dilution; L = 10^5 dilution; SW = untreated control. Data points represent (L-D) treatment means.

particulate phase resulted in significantly higher production rates at 10^3 dilution (Fig. 3B). Long-term exposure in the liquid phase of the synthetic mud resulted in a significant reduction in ^{14}C uptake at lower concentrations. ^{14}C uptake by phytoplankton exposed to a 10^3 dilution of the liquid phase of the synthetic mud for 48 h was significantly lower than that of untreated controls. By 96 h, samples exposed to a 10^4 dilution

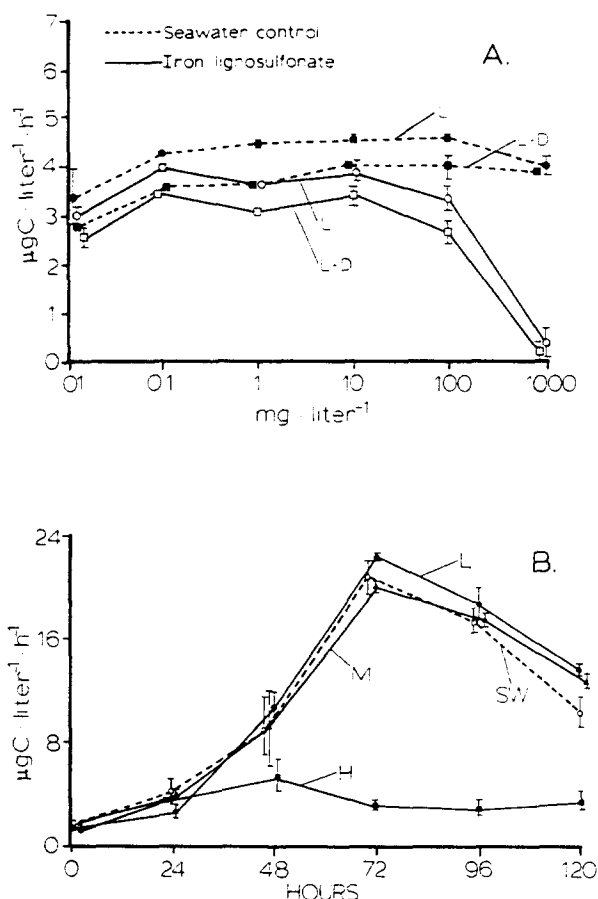


Fig. 4. Effect of iron-lignosulfonate on primary production of phytoplankton. Data points are treatment means \pm one standard deviation. A. Acute effects (<4 h exposure) of six concentrations. L = light. D = dark. Closed circles and squares are values from natural seawater incubated over pigmented filter. Open circles and squares are values from seawater with lignosulfonate added. B. Long-term effects of 120 h exposure to iron-lignosulfonate at four concentrations: H = 100 mg liter⁻¹; M = 1 mg liter⁻¹; L = 0.01 mg liter⁻¹; SW = untreated control.

of the liquid phase of the synthetic mud had a significantly lower ^{14}C uptake. However, samples exposed to a 10^5 dilution did not differ significantly from untreated seawater controls even after 120 h of exposure (Fig. 3C).

Iron-lignosulfonate (FeroCal)

Lignosulfonates are added to drilling muds primarily as thinning agents. Iron-lignosulfonate was highly pigmented and thus the ^{14}C uptake at each additive concentration was compared with a seawater control experiencing identical light occlusion. The ^{14}C uptake of natural phytoplankton assemblages exposed for less than 4 h to 1 mg of iron-lignosulfonate per liter or greater was significantly lower ($P < 0.05$) than that of untreated controls (Fig. 4A). At lower additive concentrations, no significant differences between experimental and control treatment groups were observed.

The ^{14}C uptake of phytoplankton exposed for 48 h to high concentrations of $100 \text{ mg liter}^{-1}$ of iron-lignosulfonate was significantly lower than that of untreated seawater controls ($P < 0.05$; Fig. 4B). Concentrations of 1 mg iron-lignosulfonate per liter or less did not significantly reduce primary production and slightly, but significantly ($P < 0.05$), enhanced production at 120 h.

Calcium-lignosulfonate

Calcium-lignosulfonate affected primary production similarly to iron-lignosulfonate. ^{14}C uptake (both L and L-D) was significantly different from that of seawater controls ($P < 0.05$) only at high concentrations of 1000 mg of calcium-lignosulfonate per liter (Fig. 5A). We did not investigate the long-term effects of this additive.

Chrome-lignosulfonate

^{14}C uptake of phytoplankton (both L and L-D) was significantly lower ($P < 0.05$) at concentrations of 1000 mg of chrome-lignosulfonate per liter or greater (Fig. 5B). Long-term effects were not investigated.

Paraformaldehyde

Exposure to paraformaldehyde, a biocide in drilling muds, at concentrations of 1 mg of paraformaldehyde per liter or greater, reduced ^{14}C uptake of phytoplankton to zero within 24 h. At concentrations of 0.01 mg of paraformaldehyde per liter, however, primary production was

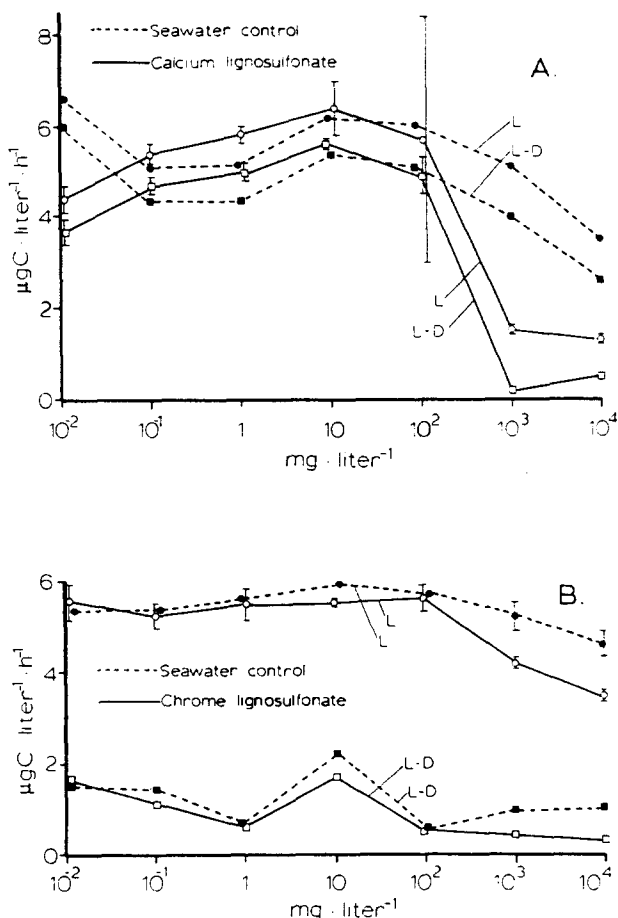


Fig. 5. Acute effects of calcium-lignosulfonate (A) and chrome-lignosulfonate (B) on primary production of phytoplankton using pigmented filters to control for light occlusion. Legend as in Fig. 4A.

not significantly different from that of seawater controls even after exposure for 120 h (Fig. 6).

Barium

BaSO₄, a major component of drilling muds, is highly insoluble. We compared the ¹⁴C uptake of phytoplankton exposed to BaSO₄ at full saturation (BaSO₄ added in excess to experimental vessels) over a 120-h period with that of seawater controls. No significant reduction or enhancement of primary production was observed (Fig. 7).

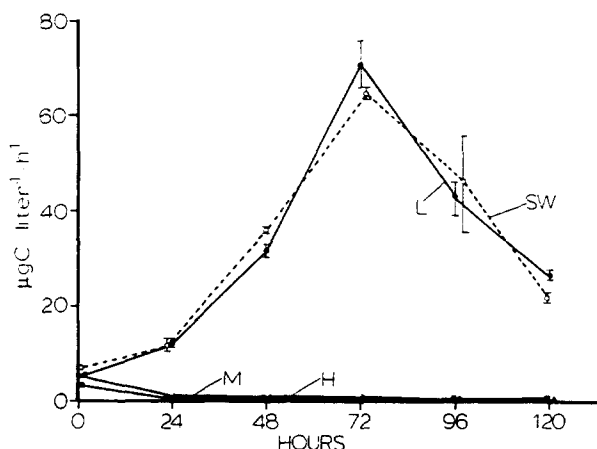


Fig. 6. Long-term effects of paraformaldehyde on primary production of phytoplankton over 120 h exposure at four concentrations. Data points are Light-Dark treatment means \pm one standard deviation. H = 10 mg liter⁻¹; M = 1 mg liter⁻¹; L = 0.01 mg liter⁻¹; SW = untreated control.

Enhancement of ¹⁴C uptake

Used drilling muds

Exposure to the liquid phase of the used drilling mud from the Santa Barbara Channel resulted in slight, but significant, enhancement of ¹⁴C uptake within 4 h at concentrations of 10⁶ or lower (Fig. 8A). Exposure to

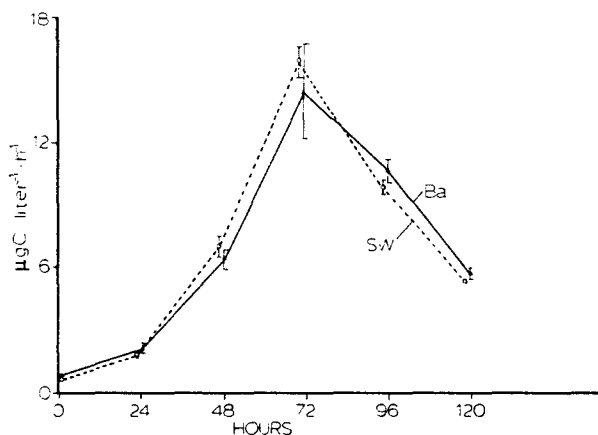


Fig. 7. Long-term effects of barium sulfate on primary production of phytoplankton over 120 h exposure at two concentrations. Data points are Light-Dark treatment means \pm one standard deviation. Ba = 100% saturated; SW = untreated control.

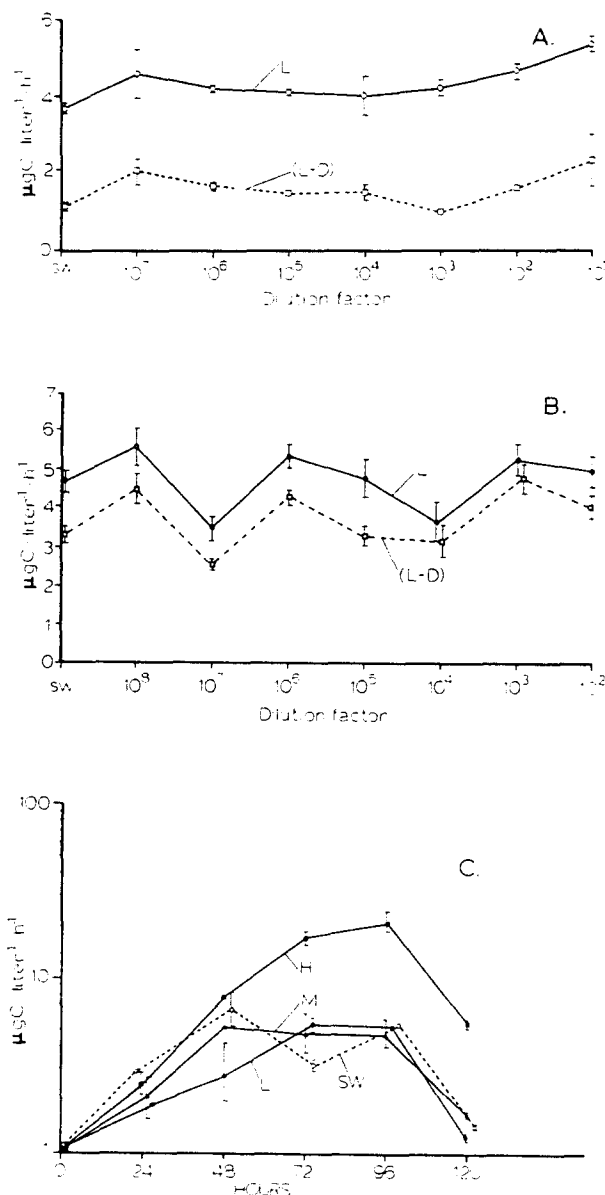


Fig. 8. Mean (\pm one standard deviation) effects of used drilling mud on primary production of phytoplankton. A. Acute effects of the liquid phase after less than 4 h exposure. L = light. D = dark. B. Acute effects of the suspended particulate phase after less than 4 h exposure at seven concentrations. C. Long-term effect of 120 h exposure to used drilling mud at four concentrations. H = 10⁻⁴ dilution; M = 10⁻⁶ dilution; L = 10⁻⁸ dilution; SW = untreated control.

the suspended particulate phase produced variable productivity but did not enhance primary production at any dilution (Fig. 8B). Long-term exposure to the liquid phase of the used muds at 10^4 dilution resulted in an order of magnitude enhancement of ^{14}C uptake, relative to that of untreated seawater controls, by 72 h. Exposure to lower concentrations of the liquid phase did not significantly affect primary production (Fig. 8C).

Drispac

Drispac, a polyanionic polymer, serves as a viscosifier in drilling muds. We found no significant effects on the ^{14}C uptake of phytoplankton exposed for less than 4 h to concentrations of 0 to 1000 mg of Drispac per liter. After exposure times of 120 h, the ^{14}C uptake of Drispac-treated samples did not differ significantly from that of seawater controls except at the lowest concentration (1 μg of Drispac per liter) which enhanced primary production by about 50% ($P < 0.05$; Fig. 9).

We examined the phytoplankton composition of samples after chronic exposure to a few of the additives and muds. Figure 10 shows the relative proportions of pennate and centric diatoms and of naked and armored dinoflagellates in samples exposed for 120 h to additives at medium concentrations. Exposure to X-Pel-G, barium and low levels of paraformaldehyde did not significantly alter the composition of the phytoplankton (Fig. 10 A, B and C). Likewise, although incubation in the

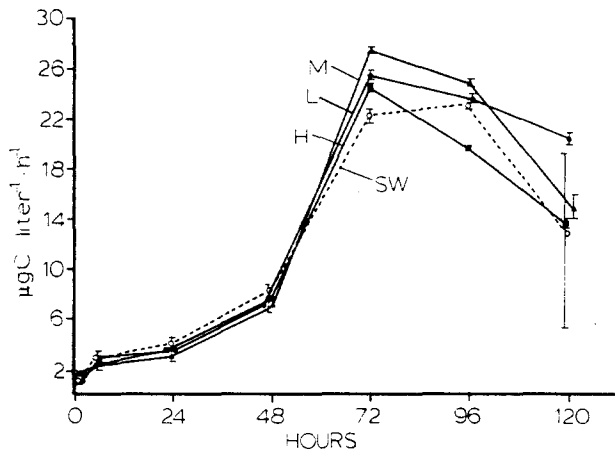


Fig. 9. Mean long-term effects (\pm one standard deviation) of Drispac on primary production of phytoplankton exposed for up to 120 h at three concentrations. H = 10 mg liter⁻¹; M = 0.1 mg liter⁻¹; L = 0.001 mg liter⁻¹; SW = untreated control.

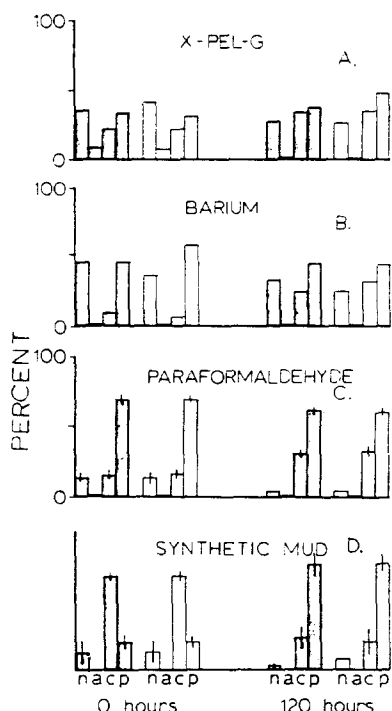


Fig. 10. Per cent (\pm standard deviation) of the total number of phytoplankton cells represented by each major taxon before and after 120 h exposure to mud additives. Shaded area shows composition of phytoplankton population in untreated control. Unshaded area shows phytoplankton composition in treatments containing additives (X-Pel-G = 1 mg liter⁻¹, Ba = 100% saturation, paraformaldehyde = 0.01 mg liter⁻¹; synthetic mud = 10⁴ dilution). n = naked dinoflagellates; a = armored dinoflagellates; c = centric diatoms; p = pennate diatoms.

laboratory significantly altered the composition of untreated seawater controls, identical changes were seen in phytoplankton samples exposed to the liquid phase of the synthetic muds at concentrations ranging from dilutions of 10³ to 10⁵ (Fig. 10D, only 10⁴ dilution shown) indicating that synthetic muds had no significant effect upon phytoplankton composition.

DISCUSSION

Discharge of drilling muds into the ocean results in substantial dilution of potentially toxic components with natural seawater. Discharged muds and cuttings form a 'lower' plume which rapidly descends until it reaches

the sea floor or becomes neutrally buoyant due to mixing with seawater and loss of solids from settling. An upper or buoyant, plume, containing about 5% to 7% of the total discharge (Ayers *et al.*, 1980), is formed by turbulent mixing of the lower plume with seawater. In water columns shallower than 80 m, the upper plume is of primary concern in determining the fate of discharges in the water column. Many field studies have traced the dispersion of materials in the buoyant plume. Generally, dilution by a factor of 10^6 yielding suspended solid concentrations less than 1 mg liter^{-1} occurs within 100 to 200 m of the discharge point within less than 1 h after discharge (see National Research Council, 1983, for review). Under high discharge rates of 1000 barrels an hour suspended solids reach background levels approximately 1500 m from the discharge source (Ayers *et al.*, 1980). The time required for a pollutant to reach such ambient levels depends upon current speeds and turbulent mixing processes and is important in assessing the potential exposure of planktonic organisms to potentially deleterious substances. Where currents are fast and produce rapid dilution, phytoplankton would be exposed to above ambient levels of muds and additives for a few minutes to hours. When currents are extremely slow ($< 1 \text{ cm s}^{-1}$) exposure to low levels of pollutants may occur for 2 to 3 days at most. Thus, the exposure times and additive concentrations used in this study represent upper limits for potential exposures of phytoplankton in nature.

Most of the additives had no significant effect on the ^{14}C uptake of natural phytoplankton communities exposed for up to 5 days to concentrations much higher than would persist for this length of time in nature. Our data indicate that neither long-term exposure to low concentrations nor short-term exposure to high concentrations of barium, iron-lignosulfonates, used drilling mud from the Santa Barbara Channel and the reference drilling mud reduces primary production of natural phytoplankton. These data suggest that these substances would have little impact on the production of natural assemblages of phytoplankton in the vicinity of drilling platforms.

Two additives, Soltex and X-Pel-G, did significantly reduce primary production of phytoplankton after long-term exposure (96 to 120 h) at concentrations of $10 \mu\text{g liter}^{-1}$. Four-hour exposures to high concentrations of these additives had no effect, indicating that initial discharge of muds containing these additives would not alter primary production. It is highly unlikely, however, that concentrations of these additives would persist at even $10 \mu\text{g liter}^{-1}$ for 96 h. Dilution would be too great even in areas of relatively little mixing (National Research

Council, 1983). Thus, our data would indicate that these additives, although potentially detrimental, would probably not impact phytoplankton in the vicinity of discharge sites.

Used drilling mud from the Santa Barbara Channel slightly enhanced primary production within 4 h of exposure even after dilution by 10^7 . Such dilutions are within the range and time scale phytoplankton might encounter during discharging of muds and cuttings into the ocean. However, our measurements of primary production after long-term exposure to low concentrations of the used muds indicate that this enhancement does not persist. Thus, it is unlikely that used drilling muds similar to those studied here would significantly increase primary production in the vicinity of offshore platforms.

The additive, Drispac, also enhanced primary production, particularly at low concentrations. Some component of both the used muds and Drispac may affect the metabolism, membrane permeability, or other unknown cellular characteristics of the phytoplankton, resulting in enhancement of production. The mechanism by which these substances enhance production is not known.

Surprisingly, most of the additives which did reduce production of phytoplankton at higher concentrations did not affect the taxonomic composition of the phytoplankton relative to seawater controls. Apparently, deleterious effects are experienced similarly by the major taxonomic categories investigated. This data indicates that major changes in phytoplankton composition due to exposure to drilling muds and additives would not be expected near discharge sites.

The absolute value of the ^{14}C uptake of phytoplankton in this study varied considerably between additives and over time for each additive. Seawater was collected for various experiments over a 6-month period and much of the variability between experiments probably resulted from natural variability in the quantity and growth state of the phytoplankton when collected. Most 5-day incubation experiments showed a marked increase in production after the first 2 to 3 days, followed by a marked decrease. Normal growth, followed by nutrient limitation, may have produced this pattern.

In summary, our data suggest that the primary production of natural assemblages of marine phytoplankton in the Santa Barbara Channel area will not be reduced by initial exposure to discharged drilling muds containing the additives studied here. Moreover, considering the rapid dilution which occurs immediately after discharge, such phytoplankton

are unlikely to experience reduction in primary production from long-term exposure. We emphasize, however, that our results are relevant only for primary production under the experimental conditions described herein. The effects of muds and cuttings on the growth, reproduction and other metabolic characteristics of phytoplankton and the effect of exposure for weeks or months to minute concentrations of additives potentially retained in the water column need further investigation.

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